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Magnetic domains studies in strongly and weakly exchange coupled Co/NiO bilayers

L. SMARDZ[1*], H. NIEDOBA[2], K. SMARDZ[3]

[1]Institute of Molecular Physics, Polish Academy of Sciences, Smoluchowskiego 17, 60-179 Poznań, Poland

[2]GEMaC de l'Université de Versailles, 45, av. Des Etats-Unis, 78035 Versailles, France

[3]Institute of Materials Science and Engineering, Poznań University of Technology, M. Skłodowska-Curie 5 Sq., 60-965 Poznań, Poland

Results of the Auger electron spectroscopy measurements with depth profiling showed that at the Co–NiO interface only oxygen is present, making it very likely that only NiO is formed and no other nickel or cobalt compounds, which grow apparently with smaller probability. It has been also found that the average exchange coupling energy for the Co–NiO interface strongly depends on the preparation conditions. For the Co layers with strong interface exchange coupling, we have observed large uniform domains and 180° walls. On the other hand, the Co layers with the weak interface coupling showed large domains with a strong ripple structure and non-uniform 180° walls.

Key words: exchange biasing; unidirectional anisotropy

1. Introduction

Magnetic bilayers containing antiferromagnetic (AFM) transition metal oxides have received considerable interest in recent years due to the exchange biasing effect [1–7]. From the technological point of view, this phenomenon plays an important role in advanced devices such as magnetic read heads [2] and magnetic memory cells [3]. Despite extensive studies, however, the exchange bias is still poorly understood, largely due to the lack of techniques capable of providing detailed information about the arrangement of magnetic moments near interfaces.

The exchange biasing is attributed to the interfacial exchange interactions between spins of the ferromagnetic (FM) layer and spins of the AFM domains in the AFM layer. Originally, it was thought that the AFM spins order in single domains with all

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*Corresponding author, e-mail: smardz@ifmpan.poznan.pl

interfacial AFM spins perfectly aligned in a single direction parallel to the FM spins, resulting in a net moment due to the uncompensated antiferromagnetic spins at the interface. However, measurements show that the biasing fields are typically one or two order of magnitude smaller than expected [5]. Theoretical work supported by neutron diffraction suggests domain formation resulting from a 90° coupling between AFM and FM moments [3]. On the other hand, direct measurements of the uncompensated spins at the surface of CoO layers in CoO/MgO and CoO/$Ni_{81}Fe_{19}$ superlattices [4] were carried out. It was found that approximately 1% of one monolayer of Co surface spins was uncompensated leading to the exchange biasing when CoO is used in FM/AFM bilayers. Experimental results also showed that the alignment of the ferromagnetic spins is determined, domain by domain, by the spin directions in the underlying antiferromagnetic layer [8]. In this paper, we report on the magnetic domains studies in Co layers strongly and weakly exchange-coupled to the AFM NiO layer.

2. Experimental procedure

Co/NiO bilayers were deposited onto glass and SiO_2(101)/Si(111) substrates in the temperature range 293–350 K using UHV (5×10^{-10} mbar) RF/DC magnetron sputtering. The Co layers were deposited using a DC source in an Ar atmosphere. The NiO-layer was prepared using a RF source in Ar + O_2 atmosphere. The chemical composition and the cleanness of all layers was checked *in-situ*, immediately after deposition, by transferring the samples to an UHV (4×10^{-11} mbar) analysis chamber equipped with X-ray photoelectron spectroscopy (XPS). Typical deposition rates for the Co and NiO layers were equal to 0.1 and 0.05 nm/s, respectively. After preparation of Si(111) substrate with native SiO_2(101) surface layer [7], we first deposited NiO layers. The Co layers were then grown immediately onto NiO. The top Co layers had a step-like wedge form. Wedge-shaped layers were grown by steeply moving a shutter in front of the substrate during deposition. Finally, 5 nm Cu cap layer was deposited to prevent the oxidation of the Co layer. Selected samples were also analysed by the Auger electron spectroscopy (AES) with depth-profile analysis in order to confirm with a chemical method the actual composition of the NiO–Co interfaces.

The structure of the samples was examined *ex-situ* by standard θ–2θ X-ray diffraction with CoK_α radiation. The magnetic characterisation of the bilayers was carried out at room temperature using the magnetooptical Kerr effect and a vibrating sample magnetometer (VSM). The observation of magnetic domains and walls was carried out at room temperature using the high-resolution longitudinal Kerr effect with digital image processing.

3. Results and discussion

For the Co/NiO bilayers with $d_{Co} > 20$ nm, the high-angle X-ray diffraction patterns show an appreciable (111) texture of *fcc* Co and NiO. The average cobalt grain size in the direction perpendicular to the substrates, as determined from the Scherrer equation, are comparable to their respective sublayer thicknesses. From the exponential variation of the XPS Co-2p and Ni-2p integral intensities with increasing layer thickness, we conclude that the Co and NiO layers grow homogeneously.

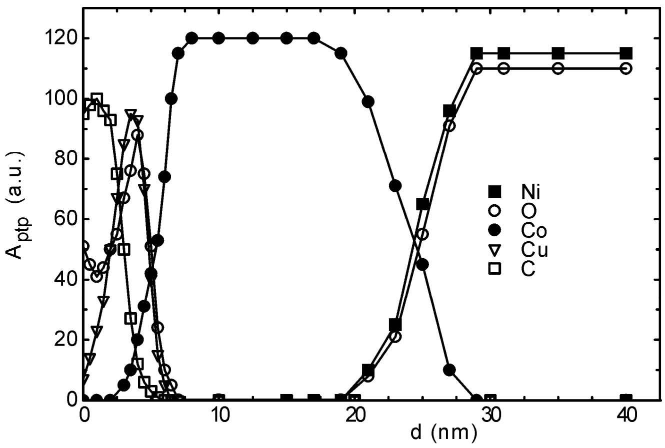


Fig. 1. AES spectrum vs. sputtering time, as converted to depth. The figure shows the peak-to-peak intensities of Co, Ni, O, and C. The surface of the sample is on the left-hand side, the substrate is on the right-hand side (not seen here)

Figure 1 shows the element-specific Auger intensities as a function of the sputtering time, converted to depth. On the left-hand side is the top of the sample and on the right-hand side is the NiO film followed finally by the substrate. Only relative intensities of five most abundant elements (carbon, oxygen, copper, cobalt, and nickel) are displayed. As can be seen, there is a relatively high concentration of carbon and oxygen on the surface of the sample. The reason of this behaviour could be due to carbonates or adsorbed atmospheric CO_2. Carbon concentration decreases towards the Cu–Co interface. At the Co–NiO interface only oxygen is present, making it very likely that only NiO is formed and no other nickel or cobalt compounds, which apparently grow with a lower probability.

Furthermore, the NiO layer has been studied *in-situ*, immediately after preparation, using X-ray photoelectron spectroscopy. In our case, the spectrum of the most intensive Ni-2p line was recorded immediately after preparation of the 40 nm NiO layer. The peak positions and the shape of the spectrum revealed formation of the single phase NiO layer during the reactive RF sputtering. The above result is very important in interpretation of magnetic properties of the NiO/Co bilayers because the exchange coupling at the interface is effective only for nickel monoxide, which is antiferromagnetic.

Results of magnetic measurements showed that the exchange-biasing and coercivity fields are inversely proportional to the Co layer thickness down to 2 nm [9]. On the other hand, an average exchange coupling energy for the Co–NiO interface strongly depends on the preparation conditions. Figures 2a and 3a show typical in-plane hysteresis loops (measured at room temperature in easy and hard direction) for the Co/NiO bilayer (d_{Co} = 4.5 nm) prepared at 350 K onto glass and at 293 K onto SiO_2(101)/Si(111) substrates.

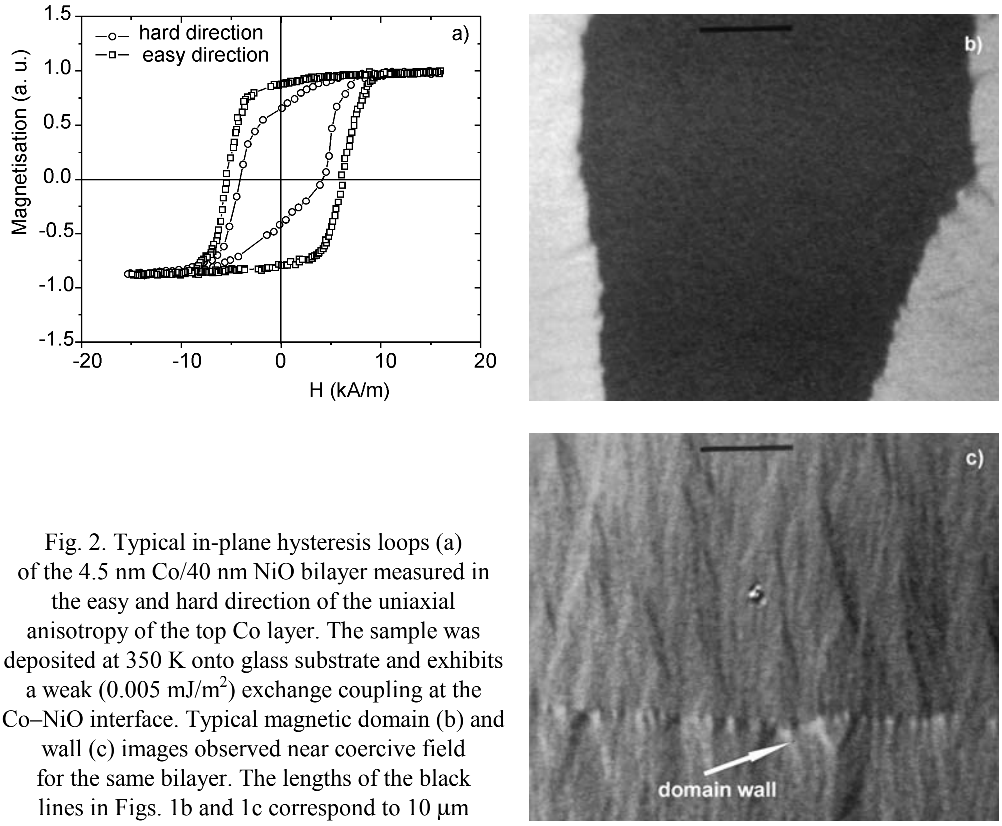
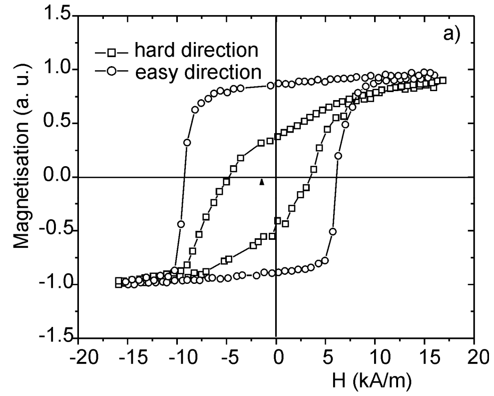


Fig. 2. Typical in-plane hysteresis loops (a) of the 4.5 nm Co/40 nm NiO bilayer measured in the easy and hard direction of the uniaxial anisotropy of the top Co layer. The sample was deposited at 350 K onto glass substrate and exhibits a weak (0.005 mJ/m^2) exchange coupling at the Co–NiO interface. Typical magnetic domain (b) and wall (c) images observed near coercive field for the same bilayer. The lengths of the black lines in Figs. 1b and 1c correspond to 10 μm

The Co layer exhibits weakly (Fig. 2a) or strongly (Fig. 3a) displaced from the origin and broadened hysteresis loops compared to those measured for the Co layer of the same thickness but without the antiferromagnetic NiO layer. The value of this displacement (H_{EB}) defines directly the exchange-biasing field. The hysteresis loop experiences a field offset that opposes the field direction in which the system has been cooled through the Neél temperature of NiO. In our case, the bilayer was cooled in a magnetic field of about 400 kA/m. As the origin of these effects, the exchange coupling between the spins of the ferromagnetic Co atoms and the spins of the Co ions in the antiferromagnetic NiO is invoked.

The coupling energy determined for the samples deposited at 350 K onto glass substrates was very small and equal to about 0.005 mJ/m^2. On the other hand, the bilayers prepared at 293 K onto SiO_2(101)/Si(111) substrates showed the average interface coupling energy as large as 0.04 mJ/m^2 [9]. Therefore, samples with strong

(0.04 mJ/m^2) and weak (0.005 mJ/m^2) coupling energy were studied by the Kerr microscopy to determine the domains and walls structures of the top Co layers during the magnetisation reversal process [10].



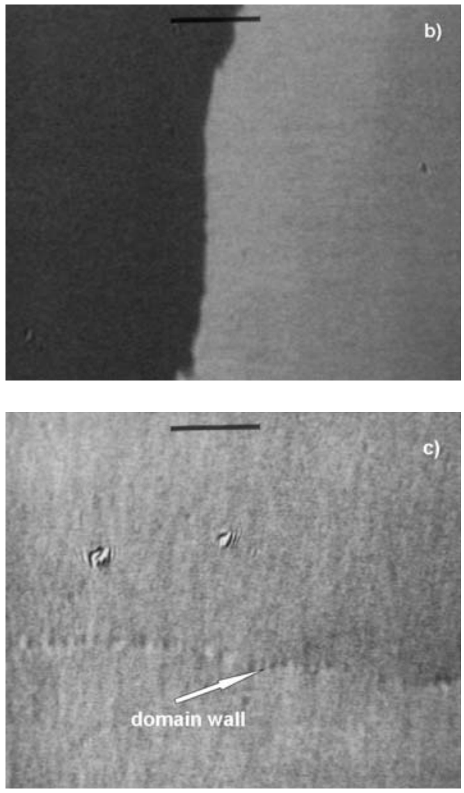


Fig. 3. Typical in-plane hysteresis loops (a) of the 4.5 nm Co/40 nm NiO bilayer measured in the easy and hard direction of the uniaxial anisotropy of the top Co layer. The sample was prepared at 293 K onto SiO_2(101)/Si(111) substrate and exhibits a strong (0.04 mJ/m^2) exchange coupling at the Co–NiO interface. Typical magnetic domain (b) and wall (c) images observed near coercive field for the same bilayer. The length of the black line in Figs. 1b and c corresponds to 10 μm

For the Co layers with a strong interface exchange coupling we have observed large uniform domains (Fig. 3b) and 180° walls (Fig. 3c). On the other hand, the Co layers with the weak interface coupling showed large domains (Fig. 2b) with a strong ripple structure and non-uniform 180° walls (Fig. 2c).

4. Conclusions

Basing on the *in-situ* XPS and AES measurements with depth profiling, we can rule out chemical impurities at the Co–NiO interface as a factor reducing the exchange energy. The Co layers with the strong interface exchange coupling showed large uniform domains and 180° walls. On the other hand, for the Co layers with the weak interface coupling we have observed large domains with a strong ripple structure and non-uniform 180° walls.

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